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Recycling lake sediment to agriculture: Effects on plant growth, nutrient availability, and leaching

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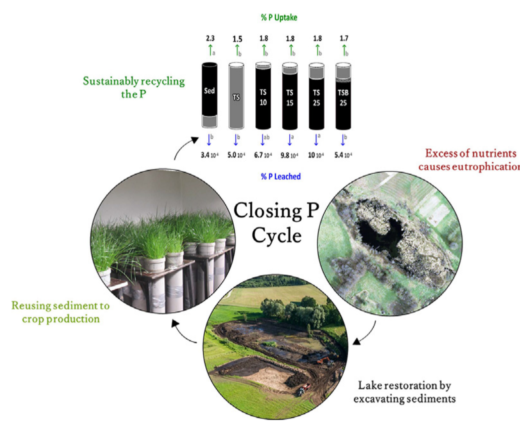
HIGHLIGHTS

- We tested excavated lake sediment as growing media for plants.
- The sediment treatments increased growth and P uptake of ryegrass.
- Al and Fe bound P was the only fraction positively correlating with plant P uptake.
- An Fe:P ratio lower than 15 in sediment may explain the high bioavailability of P.
- Biochar layer is a promising addition for reducing P and N leaching from sediment.

GRAPHICAL ABSTRACT



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ABSTRACT

Sediment removal from eutrophicated shallow lakes may not only be an effective method for lake restoration but also provides the potential for recycling nutrients from sediments to crop production. However, finding a suitable strategy for sustainably reusing the sediment remains a challenge. Therefore, current study focused on the best practices in applying the sediment from a shallow eutrophicated lake to the soil in terms of grass yield, nutrient uptake, and nutrient leaching. During a nine-month lysimeter experiment, 100-cm high columns were filled with six combinations of soil, sediment, and biochar, with or without meat bone meal organic fertilizer. Aboveground biomass, root mass distribution in soil, nutrient concentration, phosphorus (P) uptake of perennial ryegrass (*Lolium perenne* L.) along with easily soluble nutrients in the growing medium, and leached mineral nitrogen (N) and P levels were measured. Plant growth conditions were improved by sediment additions, as the yield and P uptake of ryegrass nearly doubled in treatments containing sediment compared to the control soil. While the sediment was richer in macro and micronutrients (e.g. P and N) compared to the soil, the leached N and P levels from both treatments were almost equivalent ($N < 830$ mg m^{-2} and $P < 3$ mg m^{-2}). In addition, applying a 2-cm layer of biochar between the sediment and soil reduced P and N leaching by 50%. According to the results, applying a 75-cm thick layer of sediments on agricultural sandy loam soils surrounding the lake seems a promising practice for improving plant yield and soil nutrient status without increasing of P and N leaching from soil.

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1. Introduction

The demand for phosphorus (P) by agricultural crops is mostly covered by the application of non-renewable mineral P-fertilizers or organic P-sources. The finiteness of rock phosphates and the demand increase for fertilizers during the past decade (FAO, 2015) have underlined the need for nutrient recycling in agriculture (Karunanithi et al., 2015). Further, excessive fertilizer application often goes beyond the actual demand of the crop which, in turn, leads to the transfer of P and nitrogen (N) from agricultural fields into water bodies (Yli-Halla, 2016). Agriculture is responsible for more than half of all waterborne nutrient loads in the watersheds around the Baltic Sea (Kauranne and Kemppainen, 2016). These excessive nutrients tend to accumulate to lake bottoms and can be recycled back to the overlying water column (i.e. internal nutrient loading), thus sustaining the eutrophication problem (Søndergaard et al., 2003; Kiani et al., 2020). Numerous long-term studies of lake ecosystems showed that controlling algal blooms and other symptoms of eutrophication depend on reducing inputs of a single nutrient: phosphorus (Schindler et al., 2016), emphasizing the importance of closing the P cycle. Furthermore, European countries produce approximately 200 million $m^3\ y^{-1}$ of sediment removed from waterbodies (Bortone et al., 2004). Removing sediment from eutrophicated shallow lakes may not only be an effective method for lake restoration but also provides the potential for recycling nutrients from sediments in crop production (Canet et al., 2003) or eroded coastal nourishment (De Vincenzo et al., 2019). Environmental and human health life cycle impacts of P fertilizers sourced from secondary raw materials may reportedly be lower than those of rock phosphate-derived products (Tonini et al., 2019). Dredged sediment can be re-used when concentration of contaminants are below the legislation limits (Finnish Water Directive 27.5.2011/587; Sapota et al., 2012; Nygård and Purhonen, 2019). Although the Ministry of Agriculture and Forestry in Finland recommends recycling of dredged sediment back to fields (Laakso et al., 2016), a paucity of information exists regarding the agronomic and environmental impacts of reusing sediments as soil amendment materials on agricultural lands to preserve nutrients and respond to crop demands.

The few available studies found that sediments excavated from waterbodies may, based on their properties, be richer in P than the agronomic growing medium (Harrington and McInnes, 2009; Ugolini et al., 2018; Urbaniak et al., 2019; Tozzi et al., 2020); however, there is no comprehensive study regarding plant availability of P in sediments. The decision of whether nutrients from waterbodies can feasibly be recycled to agriculture depends greatly on the nature of the sediments and soils in question. Generally, sediments are considered to be a source of available P if they have a total iron (Fe) to total P ratio lower than 15 (Jensen et al., 1992). In addition to P, other substantial benefits have been linked to sediment application such as increment of the water-retention and cation exchange capacities (Canet et al., 2003), organic matter content (OM; Canet et al., 2003; Ebbs et al., 2006; Leue and Lang, 2012; Tarnawski et al., 2015), improvement of sorption properties and nutrient contents (Canet et al., 2003: Leue and Lang, 2012; Tarnawski et al., 2015), and raising the plant yield (Canet et al., 2003; Ebbs et al., 2006). However, sediment application was also found to decrease P uptake to plants (Laakso et al., 2017) and increase the chance of heavy metal (HM) and organic contamination of the soils if not treated properly (Canet et al., 2003; Mattei et al., 2017; Tozzi et al., 2019). Moreover, the specific comparative impacts of sediment application on nutrient leaching, such as phosphate and mineral N, remain elusive and not fully documented.

A further possibility for improving the environmental sustainability of sediment reuse is combining it with biochar amendment that may potentially reduce N and P leaching from the nutrient-rich sediment and thus increase the total pool of nutrients available to plants or microbes. Recent studies reported that biochar effectively reduced nitrate (NO_3^- —N), ammonium (NH_4^+ —N), and phosphate (PO_4^{3-} —P) losses in agricultural soils (Sun et al., 2017; Shi et al., 2019). Nutrient reductions in leachate may be due to short-term NO_3^- immobilization triggered by an increase in carbon sequestration (Kolb et al., 2009; Tammeorg et al., 2012), adsorption of NH_4^+ cations by negative charges on the biochar surface, P sorption due to higher anion exchange capacity in the soil or shifts in soil pH (DeLuca et al., 2015), and P adsorption by calcium carbonate ($CaCO_3$) associated with the biochar (Kumari et al., 2014; Dari et al., 2016). Given that the benefits of biochar application varied with soil type and land use (Schomberg et al., 2013; Sun et al., 2017), there is a need for better understanding of how biochar influences plant nutrient availability and nutrient leaching from the sediment as a growing medium with possibly different physical and chemical properties and microorganisms.

The recycling of sediments and associated nutrients may offer a sustainable solution to the problem of nutrient losses from agricultural soils. With the aim of closing the agricultural P cycle, efficient ways to reuse sediment as a soil amendment on agricultural lands to preserve nutrients and respond to crop demands were identified in current study. New information on plant and soil responses to recycled sediment may improve the methods through which excavated sediments are better able to be measured and managed, and this may eventually lead to more sustainable agroecological systems. Specific objectives of this study were to: i) identify the effect of sediment application on shoot and root growth of perennial ryegrass (*Lolium perenne* L.); ii) determine the effects of different sediment application methods on nutrient availability in soil and P uptake by ryegrass; iii) explore the extent to which hardwood biochar addition can reduce P and N losses in leaching from sediment treatments.

2. Materials and methods

2.1. Study site and material collection

The study was conducted from February to October 2017 in the laboratory of the Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences in Tartu, Estonia. Sediments were collected from the 1-ha sized heavily eutrophicated Lake Mustijärv located 1 km west of Viljandi, Estonia (58°21′55.8″N 25°32′32.6″E, 65 m above sea level). Additional details about the restoration process of the lake are presented in Kiani et al. (2020). The experimental soil was an Endogleyic Lamellic Luvisol (IUSS, 2015) with a sandy loam texture.

Before excavating the sediment, a storage site was considered close to the lake shore. The top 30 cm of soil on the storage site was peeled off and piled in summer 2016. All sediment from the lake was removed and laid on the storage site. Lysimeter set-up was conducted on the first three days of February 2017, beginning with the collection of the sediment and soil (0–30 cm of the topsoil) materials from the storage site after removing the top 20-cm frozen layer. The collected materials were transported to the laboratory and stored at sampling moisture at +5 °C in darkness. Moist soils and sediments were passed through 19- and 30-mm sieves, respectively, and an effort was made to remove any stones, plant roots and earthworms. Before packing the lysimeters, the soils and sediments were homogenized using the modified cone and quartering method (Silverman et al., 1971). The mean gravimetric water contents of soil and sediment were 0.27 ± 0.01 and 2.48 ± 0.13 $m^3\ m^{-3}$, respectively.

The concentrations of heavy metals were determined in the sediment representative samples by microwave-assisted acid mineralization according to the standard method EPA 3051 and analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES, iCAP3600 MFCDuo, Thermo Fisher Scientific, Cambridge, UK; Table 1). The concentrations of polycyclic aromatic hydrocarbons (PAHs) were obtained from the sediment and biochar representative samples by sample extraction following the reflux method, being concentrated under gentle N evaporation, and analyzed by gas chromatograph-mass

Table 1
Screening criteria for metals (mg kg^{-1}), polycyclic aromatic hydrocarbon (PAHs; μg kg^{-1} dry weight), total polychlorinated biphenyls (PCBs; μg kg^{-1} dry weight), and their concentrations in sediment representative sample in 2017.

Substance	Sediment sample	Soil[a]		Compost[b]
		Threshold value	Lower guideline value	Agricultural use
Metals				
Silver (Ag)	1.21			
Arsenic (As)	9	5	50	23
Cadmium (Cd)	0.46	1	10	1
Cobalt (Co)	4.5	20	100	
Chromium (Cr)	83.6	100	200	70
Copper (Cu)	34.9	100	150	150
Iron (Fe)	17,700			
Manganese (Mn)	421			
Nickel (Ni)	12.6	50	100	60
Phosphorus (P)	3000			
Lead (Pb)	19	60	200	120
Antimony (Sb)	3.74	2	10	
Vanadium (V)	25	100	150	
Zinc (Zn)	473	200	250	500
Mercury (Hg)	0.216	0.5	2	0.7
PAHs and PCBs				
Anthracene	169	1000	5000	
2-Methylnaphthalene				
Acenaphthene	ND			
Acenaphthylene	255			
Benzo(*a*)anthracene	ND	1000	5000	
Benzo(*a*)pyrene	2618	200	2000	
Benzo(*b*)fluoranthene	202	1000	5000	
Benzo(*ghi*)perylene	433			
Benzo(*k*)fluoranthene	267			
Chrysene	162			
Dibenz(*a*,*h*)anthracene	ND			
Fluoranthene	113	1000	5000	
Fluorene	ND			
Henanthrene				
Naphthalene	720	1000	5000	
Indeno(1,2,3-*cd*)pyrene	ND			
Phenanthrene	570	1000	5000	
Pyrene	168			
Total PAH	5677	15,000	30,000	10,000
Total PCBs	<100	100	500	100

[a] The Finnish legislation sets concentration levels by each hazardous element to identify soil contamination and remediation needs. Threshold value is equally applicable for all sites and it indicates the need for further assessment of the area. In areas where background concentration is higher than the threshold value, background concentration is regarded as the assessment threshold. The second concentration level is the so-called "guideline value". If this is exceeded, the area has a contamination level which presents ecological or health risks. Different guideline values are set for industrial and transport areas (higher guideline value) and for all other land uses (lower guideline value) (Ministry of the Environment — MEF, 2007).

[b] Maximum limit values of heavy metals concentration in compost "class. A" which is suitable for agriculture in Europe (Amlinger et al., 2004).

spectrometer (GC–MS analyzer, Agilent 6890N GC/5975B MSD). For polychlorinated biphenyls (PCBs) concentrations, the samples were extracted with an acetone-heptane mixture and the heptane phase was cleaned by concentrated nitrogen acid and analyzed by GC–MS (Table 1). Using the sediment and soil representative samples, the texture was obtained by the pipette method (Elonen, 1971; Table 2); the total C and N contents were determined by Dumas dry combustion with a VarioMax CN analyzer (Elementar Analysensysteme GmbH, Hanau, Germany); the organic matter was obtained by loss-on-ignition (LOI) at 550 °C for 2 h; and electrical conductivity (EC) and pH were measured from a 1:2.5 (w/w) soil-to-water mixture (Vuorinen and Mäkitie, 1955).

The biochar was obtained in January 2017 by pyrolyzing the hardwood branches and split logs collected from the lake shore in October 2015–February 2016 including approximately 80–90% willow (*Salix*), 5–10% birch (*Betula*), and 5–10% other hardwood species (alder (*Alnus*), bird cherry (*Prunus padus* L.), and Norway maple (*Acer platanoides* L.)) in a 0.3 m^3 Kon-Tiki garden kiln (Terra Magica GmbH, Grafenrheinfeld, Germany). After pyrolysis, the biochar was soaked with a tap water:cattle slurry (7:3) mixture for activation. Following the procedure of Tammeorg et al. (2014a), the properties of biochar were characterized by determining the particle size distribution, the Brunauer–Emmett–Teller specific surface area (BET SSA), the content of volatile matter (VM), pH, ash content, $CaCO_3$ liming equivalence, the contents of carbonate–C, organic C (C_{org}), and total N and hydrogen (H; Table 2).

2.2. Lysimeter preparation

The 48 PVC tube lysimeters with walls 100 cm in height, 11 cm in outer diameter, and 0.22 cm in thickness (~8700 cm^3) were set up as a randomized complete block design with four replicates (Fig. 1a). Six growing mediums were used as the experimental treatments, either in combination with meat bone meal (MBM) fertilizer or without as the blocking factor (Fig. 1b): sediment (*Sed*): 75 cm of sediment on top of 25 cm of topsoil; topsoil (*TS*): 100 cm topsoil; *TS10*: 10 cm of soil on 90 cm of sediment; *TS15*: 15 cm of soil on 85 cm of sediment; *TS25*: 25 cm of soil on 75 cm of sediment; *TSB25*: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment. Thawed homogenized sandy loam soil and loamy sediment (Table 2) were gradually packed into the lysimeter columns. The quantity of soil or sediment for each layer was weighed and added to the lysimeter and compacted to the target bulk density for a given layer. The bulk density of soil, sediment, and biochar were 1.20, 0.33, and 0.147 g cm^{-3}, respectively, except for the first replicate where sediment packed to 0.45 g cm^{-3}. During the packing of lysimeters, subsamples of sediment, soil, and biochar materials were taken from each lysimeter, the composite samples were mixed well, and kept at −20 °C as the representative samples until they were analyzed.

Erikois-Viljo 8-4-8 (Honkajoki Oy, Honkajoki, Finland) was the organic MBM fertilizer used in the experiment, where the numbers refer to the elemental contents of N, P, and potassium (K) (w/w %), correspondingly. The 100 kg ha^{-1} MBM fertilizer (75% OM) was applied at a 3–4 cm depth from the lysimeter's surface. The amounts of macronutrients applied with the fertilizer were 100 kg N ha^{-1}, 50 kg P ha^{-1}, 100 kg K ha^{-1}, 125 kg ha^{-1} calcium (Ca), 10 kg ha^{-1} magnesium (Mg), 44 kg ha^{-1} sulphur (S), and 12 kg ha^{-1} sodium (Na). Micronutrients were also added, including 7.3 kg ha^{-1} iron (Fe), 6.9 kg ha^{-1} zinc (Zn), 3.8 g ha^{-1} boron (B), 19 g ha^{-1} cobalt (Co), 488 g ha^{-1} copper (Cu), 500 g ha^{-1} manganese (Mn), and 24 g ha^{-1} selenium (Se). The heavy metal contents were 1.3 g ha^{-1} mercury (Hg), 12 g ha^{-1} cadmium (Cd), 63 g ha^{-1} lead (Pb), and 69 g ha^{-1} nickel (Ni).

Finally, 100 seeds of ryegrass were planted at a 6–10-mm depth in each column on February 3, 2017. Each lysimeter was irrigated with 150 ml of tap water at 3- to 4-day intervals with an average amount of water applied equal to 6.2 mm of rainfall per day.

After the end of the nine-month lysimeter study, the whole soil–sediment columns were removed intact from the lysimeter pipes with the help of a cable connected to the steel plate at the bottom of the lysimeter (Fig. 1a). The soil column was removed gradually onto a table covered with a clean plastic film and was next cut into 10 equal sections, each 10 cm in height. Soil cores with roots were placed into tagged plastic bags, transferred to the University of Helsinki, and stored at +5 °C prior to the root analyses.

2.3. Plant analysis

Aboveground biomass was measured at six cutting times during the ryegrass growing season by cutting the plants 5 cm above the soil layer with scissors, drying them in paper bags at 60 °C for 72 h, and recording the dry mass. According to Miller (1997), dry biomass of the 1st cut, the mixture of the 2nd and 3rd cuts, and the mixture of the 4th, 5th, and 6th

Table 2
Sediment and soil phosphorus fractionation and physiochemical properties of sediment, soil, and biochar representative samples in the lysimeter study in 2017.

Sediment and soil			Biochar		
Property	Excavated sediment	Sandy loam soil	Property	Biochar	EBC threshold[a]
Labile P (NH_4Cl–P, mg kg^{-1})	115	<15	BET SSA (m^2 g^{-1})	198.9	>150
Fe-bound P (NaOH–P, mg kg^{-1})	830	220	pH_{H2O}	9.86	<10
Ca-bound P (HCl–P, mg kg^{-1})	1450	135	EC (dS m^{-1})	1.23	
Organic P (mg kg^{-1})	405	245	C/N (g g^{-1})	266	
Inorganic P (mg kg^{-1})	2200	270	H/C_{org}	0.019	<0.7
Total P (HCl–P, mg kg^{-1})	2600	490	Ash (g kg^{-1})	91.6	
Total Fe (mg kg^{-1})	15,000	11,000	VM (g kg^{-1})	182	
Fe/P ratio	6	22	$CaCO_3$ equivalence (g kg^{-1})	30.71	
Bulk density (g cm^{-3})	0.33	1.18	Carbonate–C (g kg^{-1})	55.3	
pH	7.23	7.36	C_{org} (g kg^{-1})	804.0	
EC (dS m^{-1})	1.58	0.16	C (g kg^{-1})	859.3	>500
Sand (%)	39.59	60.04	N (g kg^{-1})	3.2	
Silt (%)	42.17	27.28	H (g kg^{-1})	15.7	
Clay (%)	18.24	12.68	Total PAH (mg kg^{-1})	2.919	<12
LOI (%)	30.74	4.29	Particle size distribution (%)		
C (%)	17.47	2.15	0–2 mm	1.6	
N (%)	1.34	0.20	2–5 mm	2.6	
C:N	13	11	5–10 mm	32.7	
–	–	–	10–16 mm	45.9	
–	–	–	16–25 mm	17.1	
–	–	–	>25 mm	0	
–	–	–	Bulk density (g cm^{-3})	0.147	
–	–	–	water content at packing time (g g^{-1})	2.60	
–	–	–	Water holding capacity (g g^{-1} dry w)	2.31	

BET SSA: the Brunauer–Emmett–Teller specific surface area, VM: volatile matter content, PAH: concentration of total polycyclic aromatic hydrocarbons, $CaCO_3$: liming equivalence, Corg: organic carbon, H: hydrogen.
[a] Threshold values mentioned in the European biochar certificate guideline (EBC).

cuts were ground using a hammer mill with a 1-mm mesh; the ground material was dry-ashed in a muffle oven at 500 °C for 3 h; the ash was transferred into an Erlenmeyer flask with 50 ml 0.2 M hydrochloric acid (HCl), heated to aid the extraction until less than 25 ml was left; transferred quantitatively into a 50-ml measurement flask; adjusted to the volume with deionized water; and finally filtered through an ashless filter paper (Whatman, Grade 589/3, blue ribbon, pore size 2_m, GE Healthcare, UK). The concentrations of macro nutrients (P, K, S, Ca, Mg, Na) and micronutrients including aluminum (Al), B, barium (Ba), Cd, Co, chromium (Cr), copper (Cu), Fe, Mn, Ni, strontium (Sr), and Zn were determined by ICP-OES. Phosphorus uptake by the plant was calculated by multiplying the aboveground dry matter with the given P concentration.

From the four selected treatments (Sed, TS, TS25, and TSB25), the root biomass, soil bulk density, and moisture content were determined from the soil cores which were cut into sections of 10 cm (Fig. 1d). Before root washing, the bulk density and moisture content were measured by weighing the soil section, collecting a sub sample into a metal and weighing it, and finally drying it at 105 °C for 24 h and weighing again. Root washing was begun by collecting the visible roots into a container. Then, the mixture of roots and soil was washed manually through a 0.71-mm sieve with running water. Finally, the remaining material was washed with a hydropneumatic elutriation root washer (Gillison's Variety Fabrication, Benzonia, MI, USA) to separate the stones and debris. The hydropneumatic root washer separated roots from the growth medium using differences in density rather than size which prevents the loss of small roots.

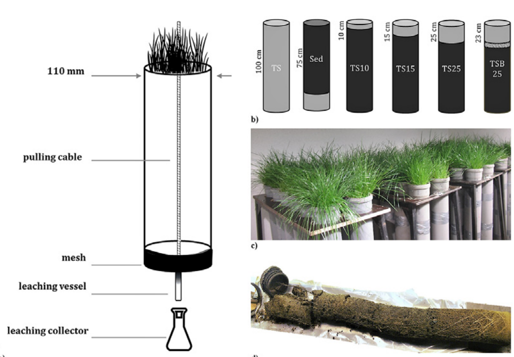

Fig. 1. Lysimeter diagram (a), growing medium treatments (b), perennial ryegrass (*Lolium perenne* L.) at the 6th harvest time (c), and a TSB25 column removed by using the pulling cable and a winch in the lysimeter experiment in 2017. Sed: sediment; TS: topsoil; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment.

2.4. Soil analysis

To determine the content of easily soluble nutrients (P, K, S, Ca, Mg, Na, B, Cu, Mn, and Zn), soil samples were taken from the top 30 cm of the lysimeter including 0–10-, 10–20-, and 20–30-cm sections at the end of the experiment and mixed to form a composite sample. Nutrients were extracted according to standard Finnish soil testing methods (Vuorinen and Mäkitie, 1955) based on an acid ammonium acetate extraction (1:10 v:v, pH 4.65). The elemental concentrations of the extracts were determined by ICP-OES. Electrical conductivity and pH of the samples were measured from a 1:2.5 (w/w) soil-to-water mixture (Vuorinen and Mäkitie, 1955).

At the end of the experiment, the P fractionation was conducted by following a modified Williams protocol by Ruban et al. (2001) to determine five P fractions according to their extractability. The extraction resulted in the obtaining of the total P (TP), organic P (OP), inorganic P (In—P), P bound to Al and Fe (hydro) oxides (Fe—P), and P bound to Ca (Ca—P). To solubilize Fe and Ca, 1 mol L^{-1} sodium hydroxide (NaOH) and 1 mol L^{-1} HCl were used, sequentially in the same aliquot (0.2 g of dried sample). With another aliquot, total P was extracted with 3.5 mol L^{-1} HCl. Using the third sediment aliquot, In—P was extracted by 1 mol L^{-1} HCl and the residual was treated at 450 °C to analyze OP. Additionally, labile P (Plab) was extracted with 1 mol L^{-1} NH_4Cl as a part of the Hieltjes and Lijklema (1980) protocol. Also, total Fe in the sediment samples was analyzed by ICP-OES.

2.5. Leachate analysis

The amount of leachate collected in the containers under the lysimeters was recorded at each harvesting time and a subsample of leachate was collected two weeks after planting, at the 1st cut, from the 1st cut to the 3rd cut, from the 3rd cut the 5th cut, and at the end of the experiment. The subsamples in 100 ml plastex bottles were kept at −20 °C until analysis. The subsamples of leachates were passed through Whatman blue ribbon filters rinsed thrice with 2 M potassium chloride (KCl) and twice with MQ water prior to filtering. The samples were analyzed for PO_4^{3-}—P, NO_3^-—N, and NH_4^+—N concentrations by spectrophotometry with an automated discrete analyzer (Gallery Plus ECM, Thermo Fisher Scientific, CA, USA). The amount of nutrients in the drained water was calculated by multiplying the concentration of each nutrient (mg l^{-1}) by the amount of leachate from the lysimeter (l m^{-2}).

2.6. Statistical analyses

Statistical analysis was performed using R v3.5.3 software. Using the Levene's and Shapiro-Wilk's tests, normality and equal variance of the whole data set was tested. The normal and homogenous variables were analyzed with Two-Way ANOVA using the growing medium and organic fertilizer as fixed factors and block as a random factor. When a significant effect was detected in the ANOVA models ($P < 0.05$), Tukey HSD tests were subsequently run to compare means and identify any grouping structure. The Kruskal-Wallis test was used for the variables with homogeneous variance but not normally distributed, and the variables that did not meet both assumptions were tested by introducing different variance structures in the *nlme* package, including stratum and exponential variance structures (Zuur et al., 2009). Network correlation among the data set was studied with Spearman analysis.

3. Results

3.1. Physicochemical properties of sediment, soil, and biochar materials

As the sediment material can be used as both fertilizer or growing medium (i.e. in small or large amounts compared with the soil volume, respectively), two guidelines were chosen to define risk levels associated with different concentrations of heavy metal and organic contaminations in sediment: firstly, standards set in the Finnish legislation for contaminated soil (Ministry of the Environment — MEF, 2007) and secondly, the limit values used for class A compost (high quality; suitable for agriculture in Europe; Amlinger et al., 2004). Almost all the measured elements in sediment had concentrations below the threshold value of contamination set by MEF, meaning that no further assessment was needed except for arsenic (As, 9 mg kg^{-1}), antimony (Sb, 3.7 mg kg^{-1}), and Zn (473 mg kg^{-1}; Table 1). The concentrations of As and Sb were higher than the MEF threshold limit (As <5 mg kg^{-1} and Sb < 2 mg kg^{-1}) but far smaller than the lower guideline values (As <50 mg kg^{-1} and Sb < 10 mg kg^{-1}), meaning no ecological or health risks occur. The Zn concentration exceeded the MEF lower guideline limit (250 mg kg^{-1}) but was lower than the threshold limit set for class A compost (500 mg kg^{-1}; Table 1). Concentrations of total PAHs and PCBs in the sediment were much lower than the MEF threshold limit (Table 1); however, the concentration of Benzo(*a*) pyrene (2618 μg kg^{-1} dry weight) was above the lower guideline value.

Sediment had an approximately eightfold higher carbon content and sevenfold higher nitrogen content than soil resulting in a C:N ratio of 13 in the sediment material (Table 2). Similarly, sediment was rich in organic matter, as indicated by a LOI value of 31% while it was 4% in the soil. While both sediment and soil had low clay contents, the majority of particles in sediment were silt (42%) and sand fraction (60%) dominated in soil (Table 2).

The produced biochar had a high C_{org} content (804 g kg^{-1}) and the low atomic (0.02) H/C_{org} ratio of the biochar (Table 2) provided evidence of a relatively high degree of carbonization during the pyrolysis based on the European Biochar Certificate (EBC, 2013). The porosity of biochar indicated by the high BET SSA value (199 m^2 g^{-1}) was greater than the minimum value of 150 m^2 g^{-1} recommended by EBC guidelines. The total PAH content of the biochar (Table 2) was below the limit set by EBC premium grade biochar (2.9 vs. 4.0 mg kg^{-1}).

3.2. Plant growth

In our study, the cumulative biomass of six cuts of ryegrass was significantly higher in treatments containing 75% to 90% of sediment versus in the soil treatment, with the highest biomass yield of

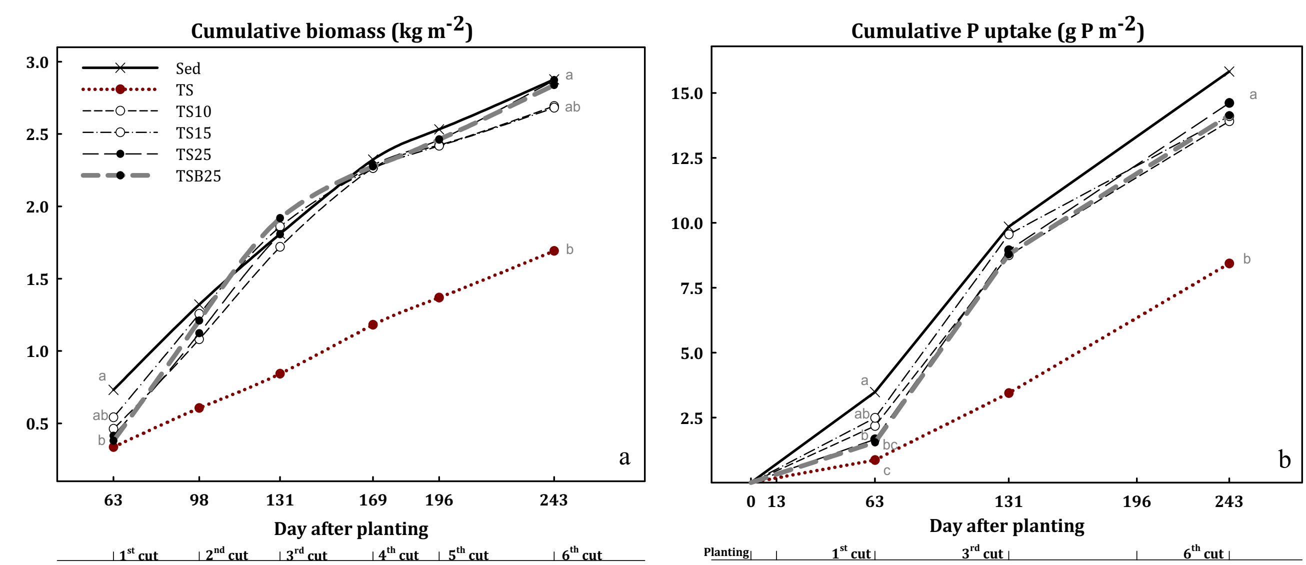

Fig. 2. Effect of growing medium on cumulative plant biomass (kg m^{-2}) in six cuts (a) and cumulative P uptake (g m^{-2}) 63, 131, and 243 days after planting (b) in the lysimeter experiment in 2017. To avoid a noisy figure, the statistical tests were only presented for 63 and 243 days after planting. Mean values within a cut followed by a different letter are significantly different at $P < 0.05$. Cumulative plant biomass and P uptake were not significantly affected by fertilizer factor and there was no significant interaction of the growing medium and fertilizer factors. Sed: sediment; TS: topsoil; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment.

Table 3
Average plant nutrient concentrations in six cuts of ryegrass in the lysimeter experiment in 2017. Data show means of four replicates across six growing medium treatments. Mean values within the growing medium treatments followed by a different letter are significantly different at $P < 0.05$. The concentrations of K, S, Mg, Al, Cd, Co, Cr, Fe, Mn, and Ni in plant dry matter (DM) were not significantly affected by growing medium.

Treatment	Plant nutrient concentration																	
	P	K	S	Ca	Mg	Na	Al	B	Ba	Cd	Co	Cr	Cu	Fe	Mn	Ni	Sr	Zn
	g kg^{-1} DM						mg kg^{-1} DM											
Sed	5.46 **a**	30.9	2.73	11.0 **ab**	6.79 **a**	5.99 **a**	30.6	19.8 **a**	2.40 **b**	0.232	0.176	0.332	9.52 **a**	65.4	16.4	0.327	8.65 **b**	138 **a**
TS	4.52 **b**	34.4	2.71	8.65 **b**	4.19 **b**	0.74 **d**	17.5	7.89 **c**	5.22 **a**	0.096	0.102	0.369	5.64 **b**	66.3	27.9	0.468	19.2 **a**	23.9 **c**
TS10	5.11 **ab**	30.3	2.47	11.9 **ab**	6.08 **a**	5.32 **a**	54.9	17.7 **ab**	3.86 **ab**	0.074	0.038	0.280	9.73 **a**	89.0	17.8	0.285	11.7 **b**	122 **ab**
TS15	5.18 **ab**	31.6	2.59	11.9 **a**	6.03 **a**	5.17 **ab**	48.5	17.0 **ab**	4.58 **a**	0.104	0.066	0.344	9.19 **a**	76.3	18.9	0.300	12.5 **b**	129 **ab**
TS25	4.79 **ab**	32.0	2.81	10.0 **ab**	5.39 **ab**	3.25 **bc**	37.3	14.5 **b**	4.38 **a**	0.070	0.027	0.225	10.22 **a**	78.6	17.1	0.403	12.8 **b**	93.2 **ab**
TSB25	4.83 **ab**	35.9	2.98	8.70 **ab**	4.17 **b**	1.64 **cd**	39.6	14.5 **b**	4.11 **a**	0.042	0.016	0.200	7.26 **ab**	71.8	18.9	0.256	10.8 **b**	77.6 **b**

Sed: sediment; TS: topsoil; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment.

2.88 kg m^{-2} observed in the Sed treatment (Fig. 2a). The yield difference between Sed and TS treatments was 70% at the end of the experiment. As a result, P uptake from Sed was significantly higher than from the TS treatment – averaging 15.8 and 8.4 g P m^{-2} from Sed and TS, respectively (Fig. 2b). On the other hand, the total root mass of ryegrass was significantly lower in Sed than in TS, helping to explain the greatest root:shoot ratio in TS equal to 0.24 ($P < 0.05$; Fig. 5). The Sed treatment also had a significantly lower root mass than other treatments at a depth of 0 to 30 cm and no significant difference among treatments was observed regarding the root mass at a depth of 30 to 70 cm.

The concentrations of macronutrients were higher in Sed than in TS with the exception of K (Table 3). This trend was especially relevant for Mg and Na ($P < 0.05$) probably due to the high salt contents of the sediments. The ryegrass grown in the Sed treatment averaged a 10% lower concentration of K ($P < 0.05$; Table 3). Among all treatments, the highest K concentration was found in TSB25 with a value equal to 35.9 g kg^{-1}, which may be linked to the high K content of biochar. Regarding micronutrients, all treatments containing sediment had significantly greater concentrations of B, Cu, and Zn in ryegrass than the soil treatment, while the reverse was true for the Sr concentration (Table 3). Also, the treatment containing biochar (TSB25) had the lowest concentrations of Cd, Co, Cr, and Ni in ryegrass ($P > 0.05$; Table 3).

Meat bone meal fertilization did not have a statistically significant effect on plant biomass, plant P uptake, or concentrations of macro- and micronutrients in plant aboveground biomass except for S, B, and Cu concentrations (Tables A and B in appendix). Applying MBM fertilizer caused 15% to 16% significant decrease in the concentration of S, B, and Cu elements in ryegrass.

3.3. Fractions of P and easily soluble nutrients in growing mediums

The total P concentration in the 30–40-cm layer of the TS treatment was only 20% of that in treatments containing sediment material (Fig. 4). After collecting six cuts of ryegrass, the labile P, Fe—P, and Ca—P fractions significantly lost approximately a quarter of their pool in the soil, while the reverse was true for the OP fraction (11% increase), which contributed the greatest percentage of TP in the soil ($P < 0.05$; Fig. 4). However, the changes in P fractions in the sediment were negligible (≤5%) except for labile P, which declined from 115 to 55 mg P kg^{-1} by the end of the experiment. The ratio of Fe to P did not change significantly during the experiment and averaged of 20 and 6 in the soil and treatments containing sediment, respectively (Table D in appendix). The contribution of Fe—P was significantly lower in TS15, TS25, and TSB25, and the share of Ca—P was higher than in the Sed treatment. Moreover, Fe—P was the only fraction that had a significant positive correlation with plant P uptake, while Ca—P positively correlated with leached phosphate (Fig. 6), which could be due to dissolution of the Ca—P, as sediment decreased the pH of the growing medium. Applying MBM did not have a significant effect on the total P and various P fractions in the 30–40-cm layers of the treatments (Table D in the Appendix). However, the growing medium × fertilizer interaction was significant regarding labile P, where the fertilizer addition increased the labile P content of the TSB25 treatment.

The sediment material increased the content of easily soluble macro- and micronutrients at the depth of 0 to 30 cm of all treatments containing sediment, except for K and Mn (Table 4). The Sed treatment had a significantly greater amount of easily soluble P, S, Ca, Mg, and Na compared to the TS, while the K content was 59% lower in Sed. In general,

Table 4
Chemical properties of the growing medium treatments in the 0–30-cm layer of the lysimeter in 2017. Samples were collected at the end of the experiment. Data show means of four replicates across six growing medium treatments. Mean values within the growing medium treatments followed by a different letter are significantly different at $P < 0.05$.

Treatment	EC mS cm^{-1}	pH	Acid ammonium acetate extractable (g m^{-3} soil)									
			P	K	S	Ca	Mg	Na	B	Cu	Mn	Zn
Sed	1.74 **a**	7.19 **b**	96.6 **a**	24.1 **e**	1599 **a**	17,107 **a**	614 **a**	97.0 **a**	3.52 **a**	9.79 **a**	99 **c**	161 **a**
TS	0.26 **c**	7.67 **a**	11.7 **d**	59.0 **b**	25 **c**	2745 **e**	270 **e**	56.9 **b**	0.78 **d**	2.74 **e**	160 **a**	3 **e**
TS10	1.39 **a**	7.34 **b**	65.1 **b**	43.4 **cd**	952 **b**	11,218 **b**	556 **b**	88.5 **ab**	2.27 **b**	6.44 **b**	124 **bc**	79 **b**
TS15	0.88 **b**	7.38 **b**	56.8 **b**	41.3 **d**	361 **c**	8421 **c**	463 **c**	69.1 **ab**	1.77 **c**	5.50 **c**	133 **abc**	56 **b**
TS25	0.40 **c**	7.62 **a**	28.1 **c**	53.3 **bc**	85 **c**	4330 **de**	342 **d**	76.0 **ab**	1.03 **d**	3.48 **de**	149 **ab**	17 **d**
TSB25	0.36 **c**	7.69 **a**	27.5 **c**	81.6 **a**	62 **c**	4482 **d**	355 **d**	74.2 **ab**	0.97 **d**	3.90 **d**	151 **ab**	19 **d**
Fertility class[a]												
Good		6.2–6.6	20–33	200–350	15–50	2000–2600	200–400	60 >	0.9–1.3	5–10	75–250	6–20
Satisfactory		5.8–6.2	12–20	120–200	10–15	1400–2000	120–200	45–60	0.6–0.9	2.7–5	25–75	2–6
Poor		5.0–5.4	3–6	40–70	3–6	400–800	50–80	15–30	0.2–0.4	1.0–1.5	6–12	1.0–1.5

Sed: sediment; TS: topsoil; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment.

[a] The classification of arable soil (Viljavuuspalvelu Oy, 2008).

deficiencies of P, B, Cu, and Zn were observed in the TS treatment according to the classification of arable soils (Viljavuuspalvelu Oy, 2008). These deficiencies were improved to a good level in all treatments containing sediment. Also, both TS and Sed were K-depleted, with concentrations lower than 60 g m^{-3}, whereas, 200 g m^{-3} is the threshold for a good level. However, the treatment containing a 2-cm layer of biochar had the highest easily soluble K level, which was significantly higher than both Sed and TS treatments (Table 4). Comparing TS25 and TSB25 indicated that biochar did not significantly increase the content of other nutrients ($P \geq 0.11$) except for K. Moreover, adding sediment material significantly reduced the pH value of the growing medium (7.19 in Sed treatment vs. 7.67 in TS treatment) and increased the EC more than sixfold compared to the TS treatment (Table 4).

MBM fertilization did not have a statistically significant effect on the amount of easily soluble macro- and micronutrients in the growing medium, except for P and Cu that were significantly 19% and 14% higher in treatments receiving MBM fertilizer (Table C in appendix). The growing medium × fertilizer interaction was also significant regarding P content, where the fertilizer addition increased the P content of all treatments except for TSB25 (Table 4).

3.4. Leaching of P and N

In general, the average concentrations of PO_4^{3-}—P and NO_3^-—N in the leachate of both TS and Sed treatments were below the minimum threshold values for causing risk in water bodies set by the European Union (PO_4^{3-}-$P < 0.04$ mg l^{-1}, NO_3^--$N < 18$ mg l^{-1}; European Commission, 2010). The average values of pH and EC in leachate ranged from 8.07 to 8.56 and 1.18 to 3.36 mS cm^{-1}, respectively. The EC values decreased during the experiment, particularly in the Sed treatment from 2.62 mS cm^{-1} at the beginning to 0.88 mS cm^{-1} at the end of 5th cut, which is in the range of freshwater streams (0.05 to 1.5 mS cm^{-1}; Behar, 1997). The cumulative volume of leachate was double in the Sed treatment compared to TS ($P > 0.05$; Fig. 3a). The lowest leaching volume was collected from the TSB25 treatment, and it was significantly lower than the leaching volume in Sed. Both TS and Sed had the lowest amounts of PO_4^{3-}—P leaching (3 mg m^{-2}), while TS15 and TS25 had the greatest levels of leached PO_4^{3-}—P (8 mg m^{-2}; Fig. 3b). The treatment containing biochar reduced 47% of the P leaching, although it was not statistically significant ($P > 0.08$). Furthermore, the mineral N leaching showed a 33% numerical decrease in the Sed treatment than in the soil, whereas T10 and T15, which contained 90% and 85% sediment material respectively, had the highest leached N (1700 mg N m^{-2}; Fig. 3c). The amount of leached N was 51% lower in TSB25 compared to TS25, although this difference was not significant ($P > 0.07$).

4. Discussion

4.1. Effects of sediment application on plant P uptake and soil P pools

The dry biomass yield of ryegrass in the first three cuts of TS treatment (lysimeters filled with the agricultural sandy loam soil surrounding the lake) was in the range of the average spring yield for common cultivars in European countries (6.3 t ha^{-1}, Sampoux et al., 2011). However, applying a 75-cm thick top layer of excavated sediment significantly increased the ryegrass yield (18.1 t ha^{-1} in the first three cuts) compared with the yield from TS treatment (Fig. 2a). Subsequently, plants were able to take up significantly greater amounts of P from the sediment (16 g m^{-2}) than from soil, resulting in double plant P uptake (Fig. 2b). The sediment clearly contained more easily soluble P than the soil treatment (Table 4). Moreover, the P fractions assumed to be potentially bioavailable (i.e. labile P and Fe—P) and total P were more abundant in the Sed treatment (Table 2) and in treatments partly containing sediment (Fig. 4). Similarly, Canet et al. (2003) previously reported higher contents of available P (38 mg kg^{-1}) in the dredged sediment of Albufera Lake in Spain compared to sandy agricultural soils surrounding the lake. The clay content of 18% in the sediment used in our study was rather low and comparable to the clay content of soil (13%). Absence of fine clay material rich in Al and Fe (hydr) oxides (Sippola, 1974) may further reduce the occurrence of P adsorption by metal oxides in the sediment material (Laakso et al., 2017). This notion agrees with earlier studies reporting higher contents of available P in sediment materials with low clay contents (<20%) compared to agronomic soil (Mattei et al., 2017; Ugolini et al., 2018; Tozzi et al., 2020). However, Laakso et al. (2017) reported a very low concentration of easily soluble P (3 mg l^{-1}) in the constructed wetland sediments compared to the silty clay loam soil, although the NaOH-P was higher in the sediment than the soil. They indicated that the high contents of clay (>60%) and Al and Fe (hydr)oxides in the sediment may fix the potentially available P. Moreover, sediments are considered a source of available P if they have a Fe/P ratio lower than 15 (Jensen et al., 1992). An example of such sediments can be found in shallow Lake Harku in Estonia (163 ha), with a low Fe/P ratio (Heinsalu, 1994), which reportly has a high concentration of labile P (~116 mg P kg^{-1}; Kisand, 2008). The Fe/P ratio of 6 in the excavated sediment of Lake Mustijärv could further explain the higher content of bioavailable P in the sediment compared to the soil.

The largest P pool in the soil material was OP fraction (40%), which is within the common range in surface soil horizons (Brady et al., 2008). In sediment, however, the largest pool, with a share of 52%, was the Ca—P fraction (Table 2 and Fig. 4a) that is considered a major form in catchments dominated by alkaline soils. The significant depletion of potentially bioavailable P (i.e. labile P and Fe—P) and even Ca—P pools in the 30–40-

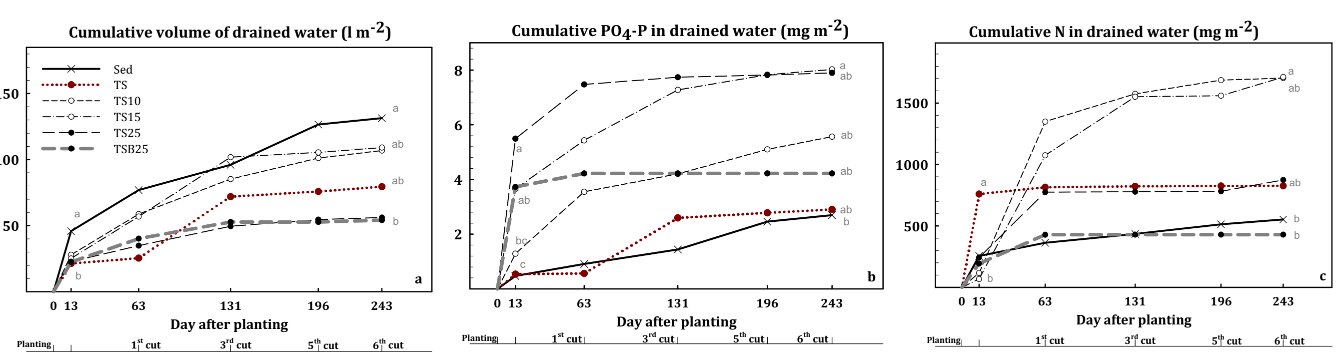

Fig. 3. Effect of growing medium treatments on cumulative leaching volume (a; l m^2), PO_4^{3-}—P (b; mg P m^{-2}), and mineral N (c; NO_3^-—N and NH_4^+-N; mg N m^{-2}) content in leaching 13, 63, 131, 196, and 243 days after planting in the lysimeter experiment in 2017. To avoid a noisy figure, the statistical tests were only presented for 13 and 243 days after planting. Mean values within a leaching collection date followed by a different letter are significantly different at $P < 0.05$. Cumulative leaching volume, and P and N in drained water were not significantly affected by fertilizer factor and no significant interaction was observed between the growing medium and fertilizer factors. Sed: sediment; TS: topsoil; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment.

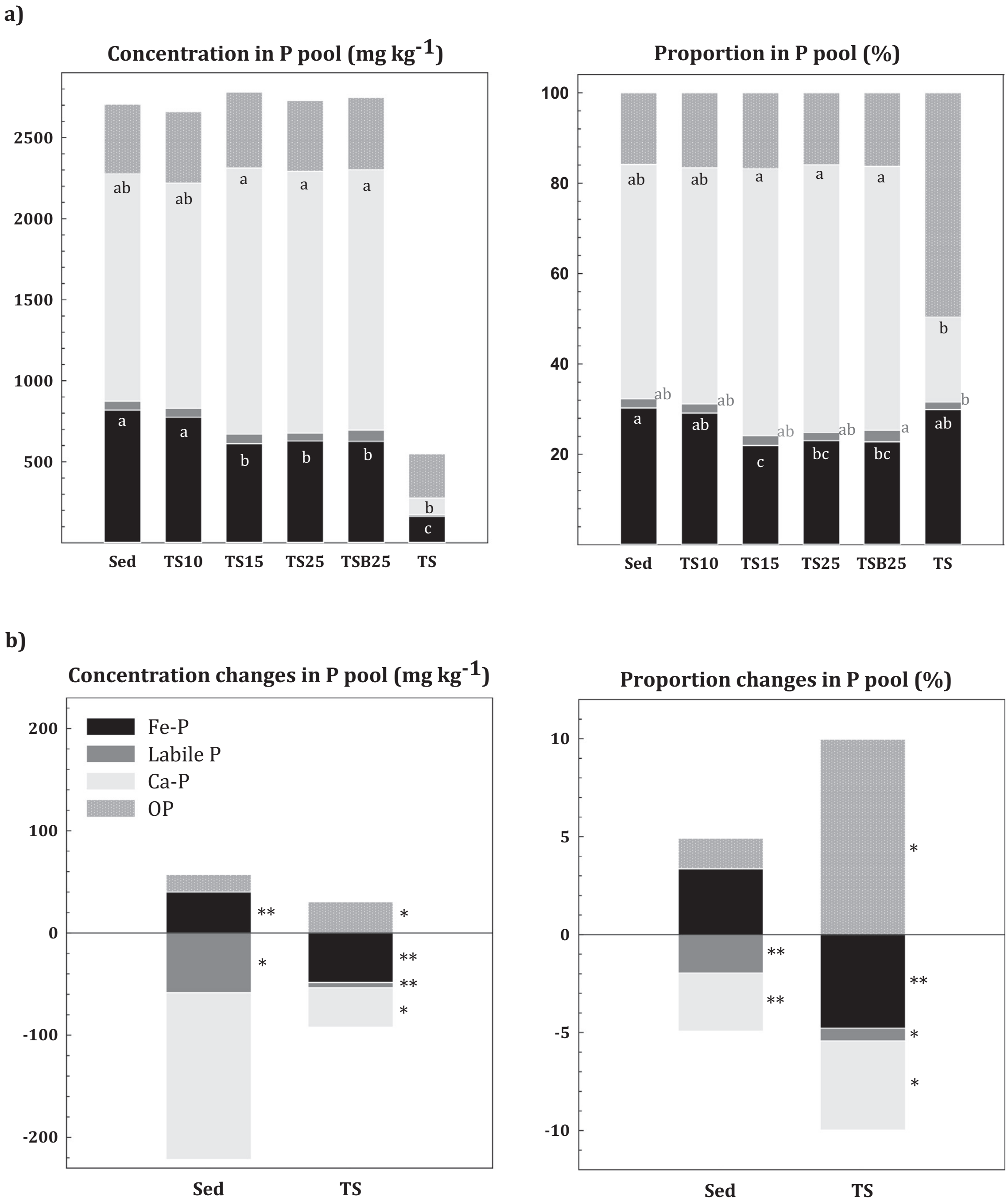

Fig. 4. (a) The concentrations of total P (TP), organic P (OP), Fe bond P (Fe—P), Ca bond P (Ca—P), labile P, and their proportions in the TP pool in the 30–40-cm layer of different growing medium treatments. Mean values within a fraction followed by a different letter are significantly different at $P < 0.05$; Sed: sediment; TS10: 10 cm of soil on 90 cm of sediment; TS15: 15 cm of soil on 85 cm of sediment; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar on 75 cm of sediment; TS: topsoil. (b) Changes in the concentrations of P fractions and their proportions in the TP pool of Sed and TS based on the starting (representative samples) and end point measurements (30–40-cm layer with no MBM fertilizer) of the lysimeter experiment in 2017. The fractions marked with one or two asterisks represent significant differences with P values < 0.05 or <0.01, respectively.

cm layer of TS may imply that plants must have taken P partly from this soil layer as well (Fig. 4b). This notion is consistent with larger total root mass ($P < 0.05$) and an order of magnitude lower easily soluble P in the 0–30-cm layer of TS treatment compared with those in the Sed treatment (Table 2; Fig. 5). Also, the OP pool increased in the 30–40-cm layer of TS, indicating a possible conversion of P into stable organic P over time (Alamgir et al., 2012) by becoming occluded within organic matter which can reduce the availability of P to plants (Brady et al., 2008).

The Fe—P pool in the 30–40-cm layer of treatments containing ≥15 cm of soil was significantly depleted more than that in the Sed treatment (Fig. 4), which is assumed to reflect the more pronounced contribution of Fe—P to P uptake from this layer. Also, in TS25 with the thickest layer of topsoil, the root mass was numerically 76% more than in the Sed treatment in the 30–70-cm layer ($P > 0.16$). Plants often proliferate roots for accessing the required nutrients deeper in the soil if their needs are not satisfied in the upper layer (Hodge, 2004). The lesser amounts of P in the upper layers (27 g P m^{-3} in TS25 vs. 87 g P m^{-3} in Sed) probably impacted the activity of roots and P uptake in the lower layers, which resulted in depletion of the Fe—P pool. This notion was further supported with robust positive correlation ($r = 0.71$; $P < 0.01$) of

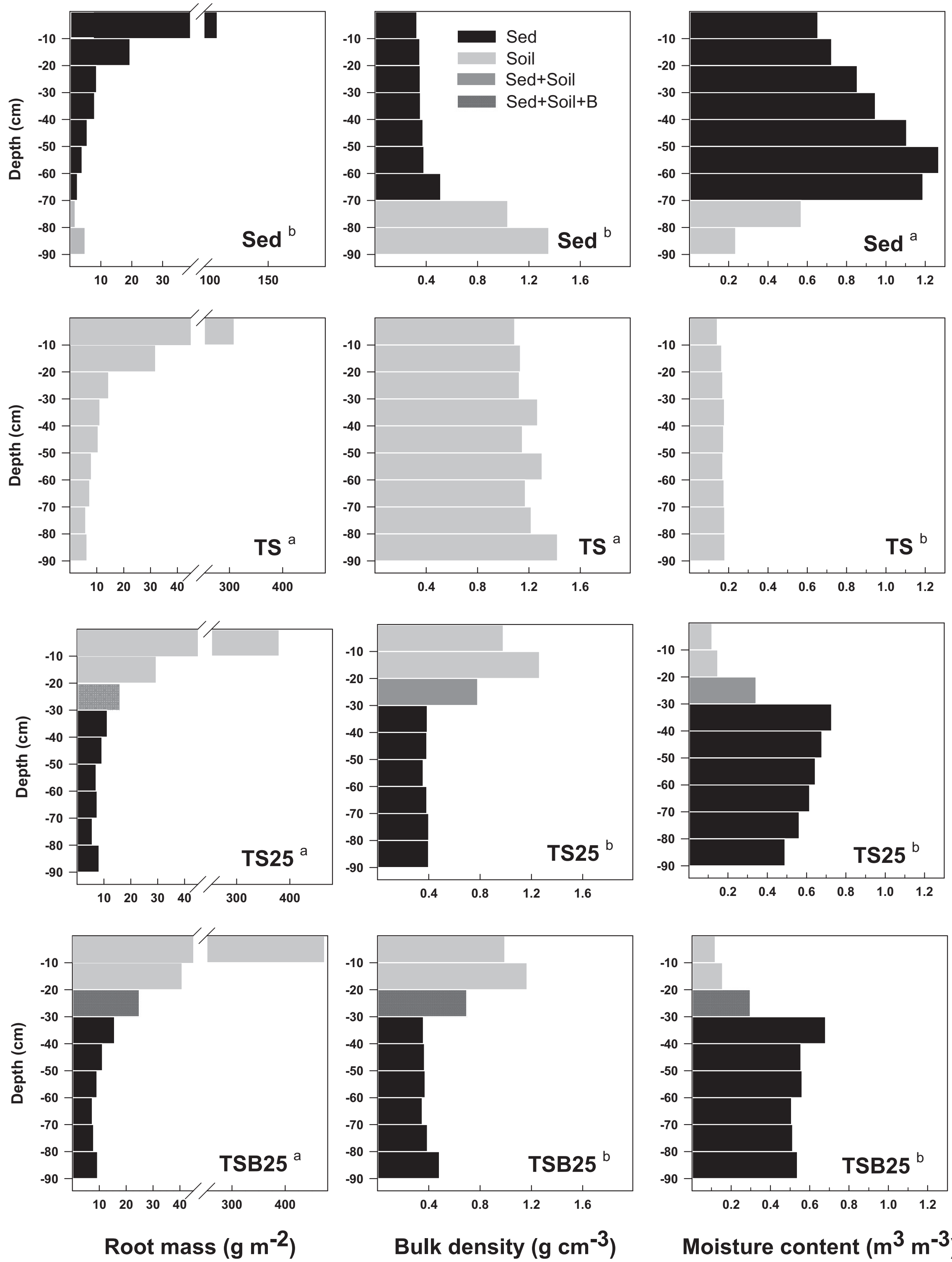

Fig. 5. Effect of growing medium on mean values of root mass (g), bulk density (g cm-3), and moisture content (m3 m-3) in the lysimeter experiment in 2017. Mean values within the whole depth of the lysimeter followed by a different letter are significantly different at $P < 0.05$. Sed had a significantly lower root mass than the other treatments at a depth of 0 to 30 cm. No significant difference was observed between TS25 and TSB25 regarding the root mass, moisture content, and bulk density at depth of 20 to 30 cm. No significant differences were observed among treatments regarding the root mass at a depth of 30 to 70 cm. Sed: sediment; TS: topsoil; TS25: 25 cm of soil on 75 cm of sediment; TSB25: 23 cm of soil plus 2 cm of biochar (B) on 75 cm of sediment.

Fe—P with P uptake (Fig. 6). In our study, of all main components of P in soil (Plab, Fe—P, Ca—P, and OP), only the Fe—P fraction positively correlated with plant P uptake. In addition, this fraction showed a notable variation during the experiment, suggesting that Fe—P is the most important fraction affecting plant P uptake.

4.2. Effects of sediment applications on ryegrass growth

In addition to P, the majority of easily soluble macro- and micronutrients were considerably more abundant in the sediment than the soil, which enhanced suitable conditions for plant growth.

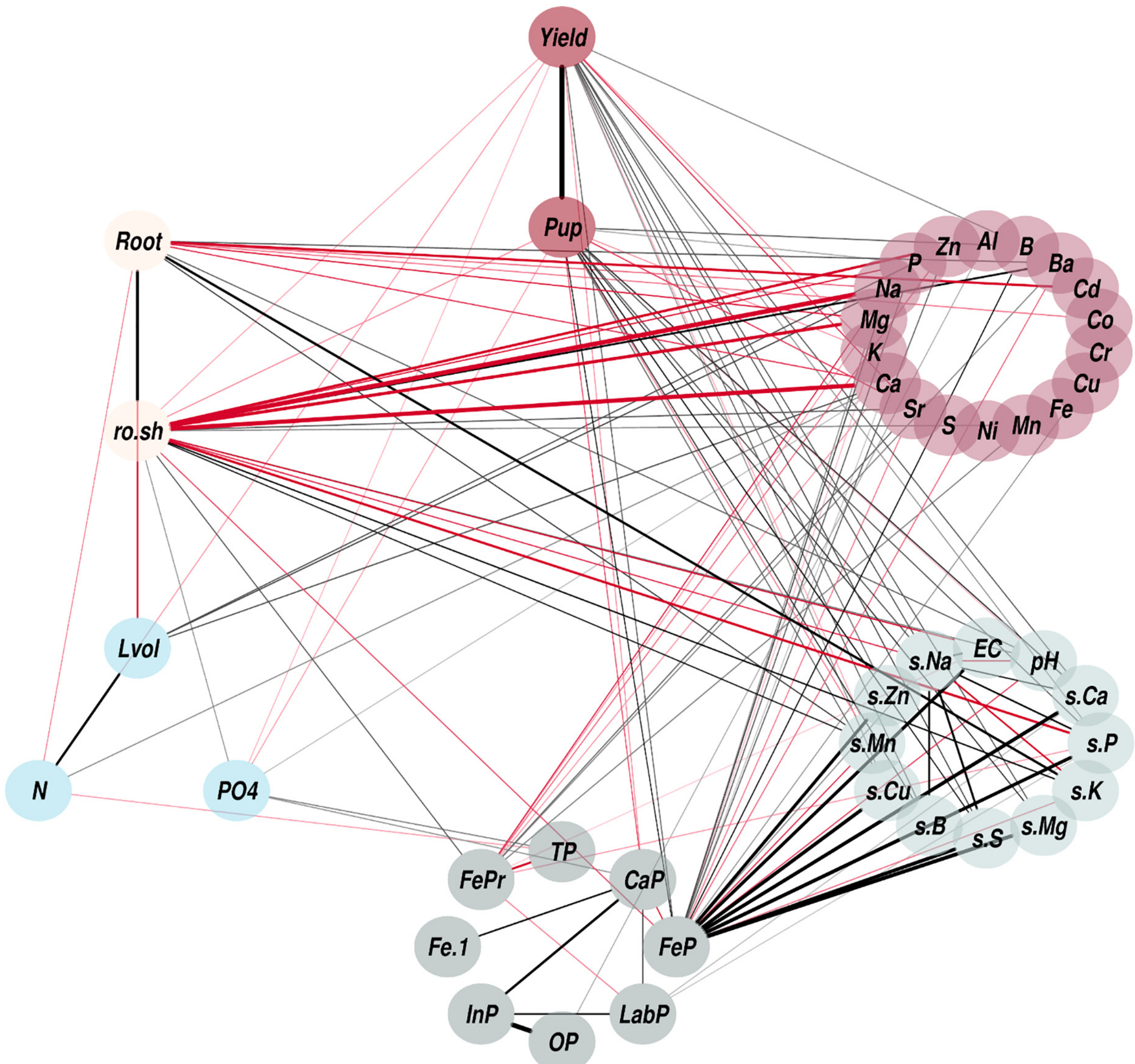

Fig. 6. Correlation network based on Spearman correlation coefficients among cumulative plant yield and P uptake (Pup), average plant nutrient concentrations, soil chemical properties at a depth of 0 to 30 cm, P fractions at a depth of 30 to 40 cm, cumulative nutrient leaching, and root data. The dataset included the values of six growing medium treatments with MBM fertilizer in four replicates accounting for 24 points for each variable except for root data (16 points). The black lines indicate positive correlations; the red lines indicate negative correlations. The thickness of the line shows the strength of the correlation. Only significant correlations were shown (cutoff value: $r > 0.40$). The correlations within plant nutrient concentrations and soil chemical properties, and also between these two categories were not shown. The label for soil available nutrients begins with the "s" letter. Abbreviations for the variables are translated as follows: labile P (LabP), inorganic P (InP), soil total Fe (Fe.1), Fe/P ratio (FePr), volume of drained water (Lvol), PO4 $^{3-}$ —P content in drained water (PO4), mineral N content in drained water (N), total root mass (root), root:shoot ratio (ro:sh). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These nutrients, likely originated from upstream agricultural soils and washed out by erosion, reached the bottom of the lake sediment and that depleted the soil (Kisic et al., 2002; Fonseca et al., 2010; De Vincenzo et al., 2019). Adding MBM fertilizer (100 kg N ha^{-1}) did not affect the yield of ryegrass (Table A in appendix) suggesting that the soil may not be N-limited. However, the organic-rich sediment material may further provide a good source of N compared to the soil, which only contained 0.2% of total N (Table 2). Nitrogen may be released from the sediment by mineralization of organic matter, which was no doubt promoted by aeration during the excavation, sieving, and packing of sediments into the lysimeters in this study. The low C:N ratio of the sediment material (13) further supports the idea of considerable microbiological decomposition of organic matter in the sediment material (Urbaniak et al., 2019). Further investigation is needed to explore the cycle of nitrogen in recycled organic sediment materials in more detail. According to the soil test results, both sediment and soil were K-deficient, but the adding a 2-cm layer of biochar improved the K status in the TSB25 treatment. Our results are consistent with earlier reports showing that the application of woody raw material biochar increased the K content of the growing medium (Jones et al., 2012; Tammeorg et al., 2014b). Moreover, the sevenfold organic matter content of the sediment compared with the soil, together with the clay content, increases the cation exchange capacity of the sediment, which increases retention of nutrient cations and could help to prevent the appearance of micronutrient deficiencies. Canet et al. (2003) also reported a clear increase in lettuce yield due to the nutrient contents of the sediments and the possible improvement of the cation exchange capacity.

Our soil test results revealed that easily soluble P, B, Cu, and Zn had low concentrations in the soil and this was considered a poor condition for inorganic mineral soil (Table 4). In addition to these nutrients, easily soluble Mg, Na, and S levels were significantly lower in the soil than in the sediment, which resulted in lower concentrations of all mentioned nutrients in plant tissues (Table 3). In keeping with this notion, the significant positive correlation ($r > 0.4$; $P < 0.01$) of ryegrass yield with soil P content (particularly Fe—P) and easily soluble Na, Mg, S, B, and Zn in the growing medium implied that the ryegrass growth was facilitated by the nutrient-rich sediment, which resulted in a higher yield (Table 3, Fig. 6). This finding is supported by recent studies reporting that the sediment mixture had comparable growth performance for holm oak seedlings (Ugolini et al., 2018), ornamental Red Robin photinia (Mattei et al., 2017), lettuce (Canet et al., 2003), and strawberry (Tozzi et al., 2020) compared to agronomic soils. Our study extends the existing literature by documenting the clear positive responses of ryegrass yield to the fertilization by a lake sediment as a nutrient source.

In regard to root mass distribution, plants grown in the Sed treatment had lower root mass in the 1-m high lysimeter compared to TS (Fig. 5). At an early growing stage, ryegrass had to take up the required nutrients from the soil section of the lysimeter in all the selected treatments except for Sed treatment. Any insufficiencies in the nutrient supply by the soil material probably triggered the plant to invest more growth into the root system to facilitate the access and adsorption of nutrients and water through the growing medium. This probably had a direct contribution to the significantly higher root mass in the top 30 cm of the column in treatments with the top layer consisting of soil (355–540 g m^{-2}) compared to the Sed treatment (134 g m^{-2}). Later, TS25 and TSB25 treatments could adsorb the nutrients from the sediment section that began at 25 cm of the column and that to some extent compensates the inadequate uptake of the majority of nutrients in the soil section (Tables 3 and 4). Plants respond to resource-rich areas and proliferate roots to increase resource uptake (Caldwell, 1994; Robinson, 1994). This is consistent with 72% higher root mass in the 20- to 30-cm layer of column in TSB25 than in the TS treatment ($P < 0.05$). Furthermore, the enhanced growing medium fertility, such as in TS25 and TSB25 treatments, may feed back into better plant growth leading to significantly greater yields in these treatments than in the TS which remained nutrient-limited. The numerically highest root:shoot ratio in the TS treatment also explained certain resource limitations (Fig. 5). It is reported that low availability of either water or nutrients commonly leads to greater root:shoot ratios, as more biomass is allocated to belowground tissues to increase the surface area for nutrient uptake (Publicover and Vogt, 1993).

4.3. Risks of mineral N and P leaching

The concentration of easily soluble P in Sed was by far greater compared to the TS treatment (Table 4); also, the highest amount of leachate was collected from the Sed treatment, especially in first harvests, which may be linked to its very low bulk density and the preferential flow pathways. However, the amount of PO_4^{3-} —P leached from the Sed treatment was not significantly different than from TS (Fig. 3b). Labile nutrients are both more prone to leaching and more readily taken up by plants (Lehmann et al., 2003). The considerably higher P uptake in the Sed treatment compared to TS, and the significant negative correlations of plant biomass with the amount of leached nutrients implies that the biomass in the sediment was abundant enough to take up large amounts of soluble P and transform them instead of the nutrients being lost through leaching (Fig. 6). Comparing the treatments containing sediment, those with the lower plant biomasses (TS15 and TS25) caused a larger amount of phosphate leaching.

The majority of leached mineral N was in nitrate form (96%) rather than ammonia form. The Sed treatment had less N in drained water compared to the TS treatment especially at the early growing stages, and this trend remained the same, resulting in, on the average, 33% less cumulative N leached from the sediment than from the soil at the end of the experiment (Fig. 3c). The total N concentrations in representative Sed samples were sevenfold of those in the soil, which emphasize the role of plant N uptake from sediment in decreasing the N leaching from the sediment. However, two treatments with the highest proportion of sediment material out of the 100-cm column (TS10 and TS15; Fig. 1b) numerically had the greatest amount of leached mineral N (1700 mg N m^{-2}) compared to other treatments. This could be due to excessive amounts of N in relation to the plant needs. Nevertheless, the TS25 and Sed treatments had the same proportion of materials but the sediment had the soil layer at the bottom of the lysimeter. Comparing these two treatments indicated that having the 25-cm soil layer beneath the sediment layer may help reduce 66% and 37% of cumulative P and N leaching, respectively ($P > 0.05$; Fig. 3).

It is noteworthy that the percentage of P leached from the total P budget of the treatment containing biochar was equivalently low as that in the soil treatment (Fig. A in appendix). Moreover, the TSB25 treatment had numerically the lowest amount of mineral N in drained water. Comparing TS25 and TSB25 treatments showed that applying 2 cm of biochar between the soil and sediment materials reduced 47% and 51% of cumulative P and N leaching, respectively (P values were 0.08 and 0.07, respectively). It has been reported that the labile C fraction in biochar may cause short-term NO_3^- immobilization leading to reduced N leaching from the soil to the environment (Kolb et al., 2009; Tammeorg et al., 2012). In addition, biochars with huge negatively charged specific surface areas after pyrolysis, can electrostatically adsorb NH_4^+ cations (Sun et al., 2017). In our study, the reduction of mineral N leaching is more probably due to $NO_3{}^-$ immobilization rather than NH_4^+ adsorption, as biochar application reduced NO_3^- —N up to 54%, while the NH_4^+ —N reduction was only 6% (Fig. B in appendix). Phosphorus retention by biochar is often described by a sorption mechanism, which may improve the P availability in soil. Also, biochar can increase plant P uptake due to its higher anion exchange capacity in soil (Novak et al., 2010; DeLuca et al., 2015), which is not the case in our study, as P uptake was lower in TSB25. Other researchers have reported that P retention in biochar-amended soils can relate to P adsorption by $CaCO_3$ associated with the biochar (Kumari et al., 2014).

5. Conclusions

Reusing excavated sediment from the eutrophicated Lake Mustijärv, with a low Fe/P ratio (6) as a form of soil amendment, improved properties of a nutrient-deficient sandy loam soil for the growth of ryegrass by increasing the availability of phosphorus and other nutrients in soil. Although the soil chemical fertility enhancement of the depleted soils alone would suffice to make this application advisable, the substantial increase in plant growth and P uptake in treatments with sediment-amendments adds further interest. Of all organic and inorganic components of soil P, the Al and Fe-bound P fraction was the most important contributor to plant P uptake. Considering the environmental impact, applying a 75-cm sediment layer on a 25-cm topsoil layer did not increase the risk of phosphate and mineral nitrogen leaching, and their average concentrations in the leachate were below the EU water quality limits for ground and surface waters. Moreover, applying a layer of biochar between the topsoil and sediment reduced ca. 50% of the total leached phosphate and mineral nitrogen quantities.

It appears that applying even a relatively thick layer of nutrient-rich lake sediment of low Fe/P ratio onto the topsoil surrounding the originated lake may be an environmentally friendly procedure for the disposal of large amounts of excavated lake materials, and sustaining agricultural crops yields without increasing the nutrients leaching from soil. Our small case study can probably be upscaled to larger lakes with similar sediment properties (e.g. Lake Harku in Estonia with approximately 1 M m^3 organic-rich sediment material). However, the promising results from this lysimeter experiment need to also be validated in a field scale, particularly regarding the questions of whether top dressing of the excavated sediment will emit greater greenhouse gas levels or whether sediment particles are more prone to erosion. Future work is also needed to find ways to recycle sediments that have a Fe/P ratio higher than 15, where P is typically not readily available for plant uptake.

CRediT authorship contribution statement

Mina Kiani: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing - original draft, Visualization. **Henn Raave:** Data curation, Methodology, Resources, Validation, Writing - review & editing. **Asko Simojoki:** Conceptualization, Data curation, Methodology, Supervision, Validation, Writing - review & editing. **Olga Tammeorg:** Conceptualization, Methodology, Resources, Validation, Writing - review & editing. **Priit Tammeorg:** Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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